THE POWER OF MYCORRHIZAL FUNGI IN BIOREMEDIATION: HARNESSING THE BENEFITS OF SYMBIOTIC RELATIONSHIP FOR A CLEANER PLANET

Abstract

This study presented the power of mycorrhizal fungi in bioremediation with the core objective of harnessing the benefits of symbiotic relationship for a cleaner planet. Mycorrhizal fungi are a type of symbiotic relationship that exist between fungi and plants, where the fungi provide the plants with nutrients, and in turn, the plants provide the fungi with energy. Some examples of mycorrhizal fungi include Arbuscular mycorrhizal fungi (AMF), Ectomycorrhizal fungi, Ericoid mycorrhizal fungi, Orchid mycorrhizal fungi, and Lichen mycorrhizal fungi. This mutualistic relationship has been shown to have significant benefits in bioremediation, the process of cleaning up contaminated environments. The fungi are able to absorb toxic metals and other pollutants from the soil, which in turn helps to reduce the levels of contamination and improve soil health. Additionally, the fungi can improve plant growth and help plants to better tolerate stress, making them ideal for use in bioremediation efforts. By harnessing the power of these fungi, it is possible to create a cleaner, healthier environment for plants and other organisms. The application of mycorrhizal fungi for a cleaner planet maybe achieved through the degradation of organic pollutants, accumulation of heavy metals and bioremediation of contaminated soils. The challenges/limitations of using mycorrhizal fungi in bioremediation includes; effectiveness dependent on pollutant type and concentration, specific species of mycorrhizal fungi used, environmental conditions and other limitations and challenges. In conclusion, the mycorrhizal fungi offer a natural, cost-effective and sustainable way to address environmental contamination and promote healthy plant growth.

Key words: Mycorrhiza; Fungi; Bioremediation; Environment

1.1 Introduction

Mycorrhizal fungi are a group of symbiotic fungi that form mutualistic associations with the roots of most plants, including vascular plants, mosses, and liverworts (Rimington, et al., 2018). In these associations, the fungi provide plants with access to water and nutrients, particularly phosphorous, in exchange for sugars produced through photosynthesis. According to many scholars, the term "mycorrhiza" comes from the Greek words "mykes," meaning fungus, and "rhiza," meaning root (Baruah, & Sahu, 2019; Lone et al., 2016; Orji et al., 2022). There are two main types of mycorrhizal associations: ectomycorrhizas and endomycorrhizas. Ectomycorrhizas are formed by fungi that grow on the outside of plant roots and form a protective sheath, or mantle, around the

root (Pandey et al., 2019). Endomycorrhizas, on the other hand, form a more intimate association with the plant roots, with the fungal hyphae penetrating into the root cells (Yadav et al., 2020).

The benefits of mycorrhizal associations to plants are numerous. For example, mycorrhizal fungi are able to access soil resources, such as phosphorous, that are otherwise inaccessible to plants (Wang et al., 2020). They also help to protect plants from soil-borne pathogens and parasites, and can improve water uptake. In addition, mycorrhizal fungi can increase the absorption of micronutrients, such as iron, copper, and zinc, by plants. Mycorrhizal fungi are also important for ecosystem processes. They are involved in the cycling of nutrients, such as nitrogen, carbon, and phosphorous, and play a crucial role in the formation of soil structure and fertility. They are also key components of the soil food web and play a role in the decomposition of organic matter (Tomer et al., 2021).

Due to the crucial role of Mycorrhizal fungi, it has gained attention in bioremediation. Tomer et al. (2021) reported that Mycorrhizal fungi have the potential to be used in bioremediation because of their ability to degrade and detoxify harmful substances in soil and water. The researchers defined bioremediation as the use of living organisms to clean up contaminated environments. Padhan, et al. (2021) documented that mycorrhizal fungi have been shown to be effective at breaking down a variety of pollutants, including heavy metals, petrochemicals, and polychlorinated biphenyls (PCBs). Some species of mycorrhizal fungi have been shown to produce enzymes that can break down organic pollutants, such as polycyclic aromatic hydrocarbons (PAHs). They are also able to absorb and accumulate heavy metals, such as lead, cadmium, and mercury, which can reduce their toxicity in the environment (Wang et al., 2020). In addition, mycorrhizal fungi can help to improve the health of contaminated soils and reduce the risk of further pollution. For example, they can improve soil structure, which can reduce erosion and runoff, and they can help to increase the uptake of nutrients and water by plants, which can reduce the need for fertilizers and other chemicals (Riaz et al., 2021).

It is from the foregoing that this present study seeks to present mycorrhizal fungi as a powerful tool in bioremediation hence seeks to harness the benefits of symbiotic relationship for a cleaner planet.

1.2 Overview of Bioremediation

Bioremediation is the use of biological processes to clean up and restore contaminated environments, such as soil, water, and air (Srivastava, 2015). This approach to environmental remediation is considered a sustainable and cost-effective alternative to traditional physical and chemical methods of pollution control (Haripriyan, et al., 2022). Bioremediation takes advantage of the natural ability of microorganisms, such as bacteria and fungi, to break down and transform contaminants into non-toxic or less harmful substances. For example, microorganisms

can degrade organic pollutants, such as oil spills and petroleum products, through the process of biodegradation. This process is facilitated by the presence of certain microorganisms that are able to utilize the contaminants as a source of energy and carbon (Haripriyan, et al., 2022).

According to Adams et al. (2015), bioremediation can also be achieved through the use of biostimulation, which involves the addition of nutrients or other substances to enhance the activity of naturally occurring microorganisms. Another approach as explained by the researchers, bioaugmentation, involves the introduction of specially selected microorganisms that are able to degrade specific pollutants. Adams et al. (2015) added that bioremediation has been used to clean up contaminated sites around the world and has been shown to be an effective method for the removal of a wide range of contaminants, including petroleum hydrocarbons, heavy metals, and persistent organic pollutants. In addition to its effectiveness, bioremediation is also considered to be a more sustainable alternative to traditional remediation methods because it does not generate waste or by-products that can further pollute the environment.

However, there are also some limitations and challenges to the use of bioremediation. For example, the effectiveness of bioremediation is dependent on the type and concentration of the pollutant, as well as the environmental conditions present at the contaminated site (Azubuike et al., 2019). Azubuike and his colleagues stressed that in some cases, bioremediation may take longer to achieve the desired results compared to traditional remediation methods.

1.3 Types of Bioremediations

Bioremediation is a diverse field that encompasses a variety of approaches to environmental remediation, including the use of plants, fungi, microorganisms, and technology. The choice of bioremediation method depends on the type and concentration of the contaminant, as well as the environmental conditions present at the contaminated site. Some of the types of bioremediations are presented as follows

1.3.1 In situ bioremediation

In situ bioremediation is a type of bioremediation that involves the treatment of contaminated soil, water, or air in place, without removing the contaminated material (Hussain et al., 2020). In situ bioremediation is considered a cost-effective and sustainable alternative to traditional remediation methods, such as excavation and disposal of contaminated material. In situ bioremediation can be achieved through several processes, including natural attenuation, biostimulation, and bioaugmentation.

i. Natural attenuation: This process involves allowing naturally occurring microorganisms to degrade contaminants in the environment. Natural attenuation is a passive approach to bioremediation that does not require the addition of any external agents. This process is often slow and may take several years to achieve the desired results, but it is considered a safe and sustainable approach to environmental remediation.
ii. Biostimulation: This process involves the addition of nutrients or other substances to enhance the activity of naturally occurring microorganisms and speed up the degradation of contaminants. Biostimulation can be used to treat a wide range of contaminants, including petroleum hydrocarbons, heavy metals, and persistent organic pollutants.
iii. Bioaugmentation: This process involves the introduction of specially selected microorganisms that are able to degrade specific pollutants. Bioaugmentation is often used to treat contaminants that are difficult to degrade through other methods, such as persistent organic pollutants.

According to Hussain et al. (2020), In situ bioremediation has several advantages over ex situ bioremediation, including lower costs, reduced energy consumption, and minimal disturbance to the contaminated site. In situ bioremediation is also considered a more sustainable approach to environmental remediation because it does not generate waste or by-products that can further pollute the environment. However, there are also some limitations and challenges to the use of in situ bioremediation. For example, the effectiveness of in situ bioremediation is dependent on the type and concentration of the pollutant, as well as the environmental conditions present at the contaminated site. In some cases, in situ bioremediation may take longer to achieve the desired results compared to traditional remediation methods (Hussain et al., 2020).

1.3.2 Ex situ bioremediation

Ex situ bioremediation is a type of bioremediation that involves the removal of contaminated soil, water, or air from the environment for treatment (Hussain et al., 2020). The contaminated material is treated outside of its original location, often in a controlled environment such as a bioreactor or a treatment pond. Ex situ bioremediation has several advantages over in situ bioremediation, including the ability to treat large quantities of contaminated material in a relatively short period of time and the ability to treat a wide range of contaminants. Ex situ bioremediation is also considered a more reliable and effective approach to environmental remediation compared to in situ bioremediation, as it allows for greater control over the conditions required for successful degradation of contaminants. However, ex situ bioremediation also has some limitations and challenges, including the need for transportation and disposal of contaminated material, the generation of waste and by-products that can further pollute the environment, and the cost and

energy consumption associated with the treatment of contaminated material (Hussain et al., 2020).

Ex situ bioremediation can be achieved through several processes, including landfarming, composting, bioreactor systems, and phytoremediation.

i. Landfarming: This process involves spreading contaminated soil on the surface of a prepared plot of land and allowing naturally occurring microorganisms to degrade the contaminants. The soil is periodically tilled to enhance aeration and increase the rate of degradation. Landfarming is often used to treat petroleum hydrocarbons, pesticides, and other organic pollutants.
ii. Composting: This process involves the treatment of contaminated material in a controlled environment, where organic matter is broken down by naturally occurring microorganisms. Composting can be used to treat a wide range of contaminants, including organic matter, heavy metals, and persistent organic pollutants.
iii. Bioreactor systems: This process involves the treatment of contaminated material in a closed system, such as a tank or a reactor, where the conditions can be controlled to enhance the degradation of contaminants by microorganisms. Bioreactor systems are often used to treat persistent organic pollutants, such as chlorinated solvents.
iv. Phytoremediation: This process involves the use of plants to extract, stabilize, or degrade contaminants in the environment. Phytoremediation can be performed ex situ, where contaminated material is removed from the environment and treated in a controlled environment, or in situ, where plants are grown directly on the contaminated site.

1.3.3 Phytoremediation

Phytoremediation is a type of bioremediation that uses plants to remediate contaminated soil, water, or air. The term "phyto" means plant, and "remediation" refers to the process of cleaning up contaminated environments (Pandey et al., 2022). Phytoremediation takes advantage of the unique properties of plants to extract, degrade, or stabilize contaminants in the environment, providing a cost-effective and environmentally friendly alternative to traditional remediation methods. Phytoremediation can be performed in situ or ex situ, depending on the location and extent of contamination. In situ phytoremediation involves growing plants directly on the contaminated site, while ex situ phytoremediation involves removing contaminated soil, water, or air from the environment and treating it in a controlled environment, such as a greenhouse or a treatment pond (Pandey et al., 2022).

There are several mechanisms by which plants can remediate contaminated environments, including:

i. Phytoextraction: This process involves the uptake of contaminants by the roots of plants and their transport to the above-ground portions of the plant. Phytoextraction is most commonly used to remediate heavy metal contamination.
ii. Phytodegradation: This process involves the degradation of contaminants by microorganisms associated with plant roots, such as mycorrhizal fungi, or by enzymes produced by the plants themselves. Phytodegradation is often used to remediate organic contaminants, such as petroleum hydrocarbons.
iii. Phytostabilization: This process involves the immobilization of contaminants in the soil, reducing their bioavailability and preventing them from leaching into groundwater. Phytostabilization is often used to remediate radionuclides, such as uranium and plutonium.

Phytoremediation has several advantages the ability to treat large areas of contaminated land, the low cost of implementation, and the potential for restoration of the site to its natural state. Phytoremediation also has the added benefit of improving the overall health of the environment, as it increases biodiversity and provides habitat for wildlife. However, there are also some challenges associated with phytoremediation, including the need for long-term monitoring and maintenance, the requirement for appropriate plant selection and species management, and the potential for the transfer of contaminants from the soil to the above-ground portions of the plant, which could pose a risk to human health and the environment (Pandey et al., 2022).

1.3.4 Mycoremediation

Mycoremediation refers to the use of fungi, specifically mushrooms, to clean up and detoxify contaminated environments (Dutta & Hyder, 2019). The process utilizes the natural abilities of fungi to decompose and break down toxic substances, such as heavy metals, petroleum, and various other organic pollutants, into less harmful compounds. Mycoremediation is a form of bioremediation, which involves the use of living organisms to remediate environmental contamination (Jindal & Thakur, 2019). Unlike other forms of bioremediation, which often rely on bacteria or plants, mycoremediation specifically uses fungi because of their unique ability to access and break down complex organic compounds. This makes them especially effective in cleaning up sites contaminated with oil, gasoline, and other hydrocarbons. The process of mycoremediation begins with the selection of appropriate fungal species based on the type of contamination present and the environment in which it is located. The fungi are then introduced into the contaminated site and begin to break down the contaminants into less toxic compounds. The process is aided by the creation of ideal conditions for fungal growth, such as moisture, warmth, and proper nutrition.

According to Dutta and Hyder (2019), Mycoremediation has several benefits including being more environmentally friendly and cost-effective.

Chemical and physical remediation methods often involve the use of harsh chemicals and high-energy processes, which can have negative impacts on the environment and human health. Mycoremediation, on the other hand, relies on natural processes and is much less intrusive, reducing the risk of further contamination or harm to the environment. Another advantage of mycoremediation is its ability to clean up a wide range of contaminants, including heavy metals, organic pollutants, and even pathogens. This makes it a versatile solution for many different types of environmental contamination. Additionally, some fungal species have been shown to have the ability to degrade persistent organic pollutants (POPs), which are toxic and highly resistant to degradation (Dutta & Hyder, 2019).

1.3.5 Microbial bioremediation

Microbial bioremediation is the use of microorganisms to remediate contaminated environments. It is a form of bioremediation that utilizes the natural abilities of bacteria, fungi, and other microorganisms to break down toxic and hazardous substances into less harmful compounds (Saeed et al., 2022). This process is used to clean up a wide range of pollutants, including heavy metals, petroleum products, and various other organic compounds. The process of microbial bioremediation begins with the selection of appropriate microorganisms based on the type of contamination present and the environment in which it is located. The microorganisms are then introduced into the contaminated site and begin to break down the contaminants into less toxic compounds. The process is aided by the creation of ideal conditions for microorganism growth, such as temperature, pH, and nutrient levels. One of the main advantages of microbial bioremediation is its ability to clean up a wide range of contaminants. Different microorganisms have the ability to break down specific types of pollutants, making them an effective solution for a variety of environmental contamination issues. Additionally, microbial bioremediation is often a more cost-effective and environmentally friendly alternative to traditional remediation methods, such as chemical and physical treatments (Azubuike et al., 2019).

Azubuike et al. (2019) added that another advantage of microbial bioremediation is its ability to access and degrade complex organic compounds, such as petroleum and other hydrocarbons. This makes it a valuable solution for cleaning up oil spills and contaminated sites contaminated with these types of pollutants. Microorganisms have also been shown to be effective in the degradation of persistent organic pollutants (POPs), which are toxic and highly resistant to degradation. However, there are also some limitations to microbial bioremediation. The process can be slow and may require significant time to achieve complete remediation. Additionally, the microorganisms used in the process may not be able to degrade all types of contaminants, particularly those that are highly toxic or resistant to degradation (Verma, & Kuila, 2019).

1.3.6 Bioelectrochemical bioremediation

Bioelectrochemical bioremediation is a form of bioremediation that utilizes the interaction between microorganisms and an electrically conductive material to clean up contaminated environments (Espinoza-Tofalos et al., 2020). The process involves the use of microbial fuel cells (MFCs), which are devices that convert the metabolic energy of microorganisms into electrical energy. The process of bioelectrochemical bioremediation begins with the selection of appropriate microorganisms based on the type of contamination present and the environment in which it is located (Lai et al., 2017). The microorganisms are then introduced into the MFCs along with the contaminated material. As the microorganisms break down the contaminants, they generate electrical energy that can be harvested and used to power various devices.

One of the main advantages of bioelectrochemical bioremediation is its ability to clean up a wide range of contaminants, including heavy metals, organic compounds, and even pathogens. This makes it a versatile solution for many different types of environmental contamination. Additionally, the process can be highly efficient and cost-effective, especially in cases where the contaminants are present in high concentrations. Another advantage of bioelectrochemical bioremediation is its ability to convert the metabolic energy of microorganisms into electrical energy. This not only makes the process more environmentally friendly, but it also has the potential to generate revenue through the sale of the electrical energy produced. In some cases, the electrical energy generated through bioelectrochemical bioremediation can even be used to power the MFCs themselves, creating a self-sustaining system. However, there are also some limitations to bioelectrochemical bioremediation. The process can be slow, requiring significant time to achieve complete remediation. Additionally, the microorganisms used in the process may not be able to degrade all types of contaminants, particularly those that are highly toxic or resistant to degradation (Espinoza-Tofalos et al., 2020).

1.3.7 Bioenergy production bioremediation

Bioenergy production bioremediation is a form of bioremediation that utilizes microorganisms to generate energy from organic waste materials (Ilshadsabah & Suchithra, 2019). The process involves the degradation of organic waste into simpler compounds, such as carbon dioxide and water, which can then be used to produce energy in the form of biogas. The process of bioenergy production bioremediation begins with the collection of organic waste materials, such as agricultural waste, food waste, and sewage. These materials are then transported to a bioreactor, where they are mixed with microorganisms that break down the organic compounds. As the microorganisms break down the waste, they generate biogas, which is comprised of methane and carbon dioxide. One of the main advantages of bioenergy production bioremediation is its ability to generate renewable energy from organic waste materials. This not only

reduces the amount of waste that is sent to landfills, but it also reduces the dependency on non-renewable energy sources. Additionally, the process can be highly efficient, producing a large amount of energy from a small amount of waste material (Ilshadsabah & Suchithra, 2019).

3. The Role of Mycorrhizal Fungi in Bioremediation

Mycorrhizal fungi play an important role in bioremediation, which is the process of cleaning up contaminated environments using microorganisms and other natural processes (Tomer et al., 2021). Mycorrhizal fungi form symbiotic relationships with the roots of plants and help to increase the plant's ability to absorb nutrients and water from the soil. This increased uptake of nutrients and water helps to promote healthy plant growth, which in turn helps to reduce the levels of contaminants in the soil (Hashem et al., 2019). In addition to their role in increasing plant growth, mycorrhizal fungi also have the ability to directly degrade pollutants in the soil. This is because they produce enzymes that can break down complex organic compounds, including many of the pollutants that are commonly found in contaminated soils. This ability to directly degrade pollutants makes mycorrhizal fungi an effective tool in bioremediation efforts. One of the key advantages of using mycorrhizal fungi in bioremediation is that they are able to thrive in a wide range of environments, including those that are contaminated with heavy metals, organic pollutants, and other toxic substances. This makes them an ideal choice for bioremediation efforts in many different types of contaminated environments. Another advantage of mycorrhizal fungi is that they are able to help reduce soil erosion, which can help to prevent further contamination of the environment. This is because the roots of plants that are colonized by mycorrhizal fungi are better able to anchor the soil, reducing the risk of erosion (Tomer et al., 2021).

3.1. Formation of Mycelial Networks

Mycorrhizal fungi form symbiotic relationships with the roots of plants and play a crucial role in bioremediation, the process of cleaning up contaminated environments using microorganisms and other natural processes (Mishra et al., 2019). One of the key ways that mycorrhizal fungi contribute to bioremediation is through the formation of mycelial networks. Mycelial networks are networks of fungal filaments that spread throughout the soil and help to promote the exchange of nutrients and water between plants and the surrounding environment. These networks can be extensive and can span large areas of soil, providing a network of channels for the exchange of water, nutrients, and other compounds. In contaminated environments, mycelial networks formed by mycorrhizal fungi can help to reduce the levels of pollutants in the soil. This is because the networks can help to distribute nutrients to plants, promoting healthy plant growth and increasing the plant's ability to absorb pollutants from the soil. Additionally, the fungal filaments themselves can directly degrade pollutants, breaking them down into

simpler compounds that are more easily absorbed by the plants (Mishra et al., 2019).

3.2 Direct Degradation of Pollutants

The direct degradation of pollutants is another important role that mycorrhizal fungi play in bioremediation, the process of cleaning up contaminated environments using natural processes and microorganisms (Anastasi, et al., 2012). Mycorrhizal fungi are capable of breaking down a wide range of pollutants, including toxic heavy metals, hydrocarbons, and other organic compounds. This degradation occurs through a number of mechanisms, including the production of enzymes and other degradation products by the fungal cells themselves. Mycorrhizal fungi produce a wide range of enzymes that are capable of breaking down a variety of pollutants, including laccases, peroxidases, and other oxidative enzymes. These enzymes can help to break down pollutants, reducing their toxicity and making them more easily absorbed by the plants (Tomer et al., 2021).

In addition to the production of enzymes, mycorrhizal fungi can also directly adsorb pollutants from the soil, reducing their bioavailability and making them less harmful to the surrounding environment. This is because the fungal cells themselves have a high affinity for certain pollutants, including heavy metals, and are capable of sequestering these contaminants within their own cell walls, reducing their bioavailability and toxicity. The direct degradation of pollutants by mycorrhizal fungi is particularly useful in contaminated environments where the levels of pollutants are high, as the fungi can help to reduce the levels of pollutants and improve soil health. In addition, the use of mycorrhizal fungi in bioremediation is a cost-effective and environmentally friendly approach, as it does not require the use of costly chemical treatments or other forms of technology. Some examples of this process are highlighted below:

i. Metal detoxification: Mycorrhizal fungi are particularly effective in removing heavy metals from contaminated soils. Heavy metals are known to be toxic to plants and other living organisms, and their removal is an important aspect of bioremediation efforts. Mycorrhizal fungi can remove heavy metals from the soil through direct adsorption, reducing their bioavailability and toxicity.
ii. Petroleum hydrocarbons degradation: Mycorrhizal fungi can also help to degrade petroleum hydrocarbons, which are a common contaminant in many contaminated environments. These fungi are capable of breaking down petroleum hydrocarbons through the production of enzymes and other degradation products, reducing their toxicity and improving soil health.
iii. Organic contaminants degradation: Mycorrhizal fungi are also capable of degrading a wide range of organic contaminants, including polycyclic aromatic hydrocarbons (PAHs) and other toxic compounds. The fungi can help to break down these contaminants

through the production of enzymes and other degradation products, reducing their toxicity and improving soil health.

iv. Synergistic degradation: The direct degradation of pollutants by mycorrhizal fungi can occur in synergy with other bioremediation efforts, such as the use of bacteria and other microorganisms. This can help to increase the efficiency of the bioremediation process and reduce the levels of pollutants in the soil more effectively.

v. Long-term effects: The direct degradation of pollutants by mycorrhizal fungi can have long-term effects on soil health, as the fungi can help to maintain the stability of the soil structure and reduce the risk of erosion. This can promote the growth of a diverse range of soil microorganisms and improve soil fertility over time (Anastasi, et al., 2012).

3.3 Improvement of Soil Health and Reduction of Pollution Risks

The improvement of soil health and reduction of pollution risks are two critical roles that mycorrhizal fungi play in bioremediation, the process of cleaning up contaminated environments using natural processes and microorganisms. Mycorrhizal fungi are a key component of healthy soil ecosystems, and their presence can help to improve soil health and reduce the risk of pollution in a number of ways (Tomer et al., 2021).

i. Soil structure improvement: Mycorrhizal fungi can help to improve soil structure by promoting the growth of a diverse range of soil microorganisms. The fungal networks that they form can help to increase the stability of the soil structure, reduce the risk of erosion, and improve soil fertility. This can have long-term effects on soil health and promote the growth of healthy plants.

ii. Increased nutrient availability: Mycorrhizal fungi are capable of improving soil fertility by increasing the availability of nutrients to plants. They can do this by forming symbiotic relationships with plant roots, exchanging nutrients between the plant and the fungus. This exchange of nutrients can help to increase the availability of essential nutrients to plants, such as nitrogen, phosphorus, and other micronutrients, improving soil fertility and plant growth.

iii. Pollution mitigation: Mycorrhizal fungi can also play a critical role in reducing the risk of pollution in contaminated environments. They are capable of adsorbing pollutants from the soil, reducing their bioavailability and toxicity. This can help to reduce the levels of pollutants in the soil, making it safer for plants and other living organisms.

iv. Phytoremediation enhancement: Mycorrhizal fungi can also enhance the effectiveness of phytoremediation, a form of bioremediation that uses plants to remove pollutants from the soil. The fungi can help to improve plant growth and health, making it easier for the plants to absorb and degrade pollutants from the soil.

4 Application of Fungal Mycorrhiza for a Cleaner Planet

Fungal mycorrhiza is a symbiotic relationship between fungi and plant roots that has been found to play a crucial role in bioremediation and soil health. The application of fungal mycorrhiza for a cleaner planet involves using these fungi to degrade and remove pollutants from contaminated environments and improve soil health. One common method of applying mycorrhizal fungi in bioremediation is through the introduction of fungal spores or plant roots colonized with mycorrhizal fungi into the contaminated soil. This can increase the population of mycorrhizal fungi and improve their ability to degrade pollutants. Additionally, mycorrhizal fungi can be isolated from the contaminated site and grown in the laboratory to increase their populations before reintroduction into the environment (Berruti et al., 2014).

Mycorrhizal fungi have been shown to be particularly effective in the degradation of persistent organic pollutants such as polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), and dioxins. They also help in bioremediation of heavy metal pollutants such as lead, cadmium, and mercury by forming a symbiotic relationship with plants, which absorb the metals and reduce their toxicity in the soil. In addition to their role in pollutant degradation, mycorrhizal fungi also help to improve soil health and structure. They increase the availability of nutrients in the soil, promote the growth of other microorganisms, and reduce the risk of soil erosion and compaction. Examples of mycorrhizal fungi species that are commonly associated with bioremediation efforts include Glomus, Rhizophagus, and Funneliformis. These fungi have a wide range of capabilities and are known for their ability to degrade a variety of pollutants, making them versatile and effective bioremediation agents (Berruti et al., 2014).

4.1 Degradation of Organic Pollutants

The degradation of organic pollutants by mycorrhizal fungi is a crucial aspect of their contribution to a cleaner planet. Organic pollutants, such as polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), and dioxins, are persistent and toxic contaminants that can cause long-term harm to the environment and human health. Mycorrhizal fungi have been found to play a crucial role in the degradation of these pollutants, breaking down complex molecules and reducing their toxicity. One of the mechanisms by which mycorrhizal fungi degrade organic pollutants is through the production of enzymes and secondary metabolites, such as laccases and ligninolytic enzymes, that break down the pollutants. The mycorrhizal fungi also play a role in promoting the growth of other microorganisms in the soil that can contribute to pollutant degradation (Tomer et al., 2021).

Another way in which mycorrhizal fungi contribute to the degradation of organic pollutants is through their ability to form symbiotic relationships with plants. The mycorrhizal fungi provide the plants with essential

nutrients and water, while the plants absorb and detoxify the pollutants in the soil. Mycorrhizal fungi have been found to be particularly effective in the bioremediation of contaminated soils, as they can grow in low-nutrient environments and survive in harsh conditions. This makes them ideal candidates for cleaning up contaminated environments and reducing the risks to human health and the environment. Examples of mycorrhizal fungi species that have been found to be effective in the degradation of organic pollutants include Glomus, Rhizophagus, and Funneliformis. These fungi are known for their ability to degrade a variety of pollutants and to form symbiotic relationships with plants, making them effective and versatile bioremediation agents (Tomer et al., 2021).

4.2 Accumulation of Heavy Metals

Mycorrhizal fungi are known to play an important role in the accumulation of heavy metals in soil. These fungi form a symbiotic relationship with plant roots, and they help to absorb and transfer essential nutrients and water to the plant. In the process, they can also accumulate and store heavy metals, such as lead, cadmium, and nickel, from the soil. This ability of mycorrhizal fungi to store heavy metals makes them useful for bioremediation, the process of using living organisms to clean up contaminated environments. The use of mycorrhizal fungi for bioremediation has several advantages (Verma & Kuila, 2019).

First, mycorrhizal fungi are naturally occurring and widely distributed in the environment, making them a readily available resource for bioremediation efforts. Second, they can tolerate high levels of heavy metals, making them ideal for use in contaminated areas. Third, they can help to reduce the bioavailability of heavy metals, reducing their potential to cause harm to the environment and human health. In bioremediation, mycorrhizal fungi can be introduced into contaminated areas, where they can absorb and store heavy metals from the soil. The accumulated heavy metals can then be harvested from the fungi and removed from the site, reducing the overall heavy metal contamination in the area. Additionally, the presence of mycorrhizal fungi can also help to promote the growth of plants in contaminated areas, which can further aid in the cleanup process by phytoremediation, the process of using plants to remove pollutants from the environment (Verma & Kuila, 2019).

4.3 Bioremediation of Contaminated Soils

Bioremediation of contaminated soils using mycorrhizal fungi is a promising approach for cleaning up polluted environments and promoting a cleaner planet. Contaminated soils pose a significant risk to human health and the environment, and conventional methods of cleaning up contaminated sites, such as excavation and soil replacement, can be expensive and impractical (Riaz et al., 2021). Bioremediation, on the other hand, is a more sustainable and cost-effective solution that

utilizes living organisms to clean up contaminated sites. In bioremediation, mycorrhizal fungi can be introduced into contaminated soil, where they absorb and store heavy metals. The accumulated heavy metals can then be harvested from the fungi and removed from the site, reducing the overall heavy metal contamination in the area. Additionally, the presence of mycorrhizal fungi can also help to promote the growth of plants in contaminated areas, which can further aid in the cleanup process through phytoremediation, the process of using plants to remove pollutants from the environment (Riaz et al., 2021).

Phytoremediation can be an effective way to remove pollutants from contaminated soils. Plants absorb pollutants through their roots and store them in their above-ground tissues. This makes it possible to remove the pollutants from the site by simply harvesting the plants. Mycorrhizal fungi can enhance the effectiveness of phytoremediation by providing plants with improved access to nutrients and water, which can increase their ability to tolerate high levels of heavy metals and improve their overall growth and health (Riaz et al., 2021).

5 Limitations and Challenges of Using Mycorrhizal Fungi in Bioremediation

While mycorrhizal fungi hold promise for bioremediation, there are also some limitations and challenges that must be addressed in order to make the most of their potential. Some of the following limitations and challenges were earlier highlighted in Mishra et al., (2019)

5.1 Effectiveness Dependent on Pollutant Type and Concentration

The effectiveness of mycorrhizal fungi in bioremediation is dependent on the type and concentration of the pollutant. Different heavy metals have different chemical and physical properties, and some may be more easily absorbed by mycorrhizal fungi than others. For example, some fungi may be more effective at absorbing cadmium than lead, while others may be better at absorbing lead than cadmium.

In addition, the concentration of the heavy metal in the soil can also play a role in the effectiveness of bioremediation efforts. At high concentrations, heavy metals can be toxic to plants and mycorrhizal fungi, making bioremediation more challenging. However, at lower concentrations, mycorrhizal fungi may be able to effectively remove heavy metals from the soil over time, allowing for bioremediation to occur. Furthermore, other environmental factors such as soil pH, nutrient levels, and temperature can also impact the effectiveness of mycorrhizal fungi in bioremediation. For example, some fungi may be better suited to soils with low pH levels, while others may be more effective in soils with higher pH levels.

5.2 Specific Species of Mycorrhizal Fungi Used

The specific species of mycorrhizal fungi used is another limitation and/or challenge in using mycorrhizal fungi for bioremediation. Different species of mycorrhizal fungi have different abilities to absorb heavy metals from contaminated soils, and some may be more effective than others. For example, some species of mycorrhizal fungi have been shown to be more effective at absorbing heavy metals such as lead and cadmium, while others may be better at absorbing other heavy metals such as zinc and copper. In addition, some species of mycorrhizal fungi are more effective at absorbing heavy metals in certain types of soils, such as sandy or clay soils, while others may be better suited to other soil types. Therefore, careful consideration of the specific species of mycorrhizal fungi used is important in order to maximize the effectiveness of bioremediation efforts. This may require conducting extensive research and trials to determine the most effective species of mycorrhizal fungi for a specific bioremediation project, taking into account the type and concentration of the heavy metal contaminant, as well as the environmental conditions of the soil.

5.3 Environmental Conditions

environmental conditions can also pose a limitation or challenge when using mycorrhizal fungi for bioremediation. The effectiveness of mycorrhizal fungi in removing heavy metals from contaminated soils is largely dependent on the environmental conditions of the soil, such as soil temperature, moisture levels, and nutrient availability.

For example, mycorrhizal fungi require specific temperature ranges and moisture levels to grow and thrive, and these conditions must be maintained in order for the fungi to effectively absorb heavy metals from the soil. In addition, mycorrhizal fungi need a sufficient supply of nutrients such as phosphorous, nitrogen, and potassium in order to grow and function effectively.

If the environmental conditions are not favourable for the growth of mycorrhizal fungi, their ability to absorb heavy metals may be limited, and bioremediation efforts may not be as effective. For example, if soil temperatures are too high or too low, the growth of mycorrhizal fungi may be suppressed, and the ability of the fungi to absorb heavy metals may be impacted.

Some specific species of mycorrhizal fungi and their temperature requirement are highlighted below

i. *Glomus intraradices*: This species is commonly used in bioremediation efforts due to its high ability to absorb heavy

metals. It grows well in soils with moderate to high levels of moisture and prefers temperatures between 20-25°C.

ii. *Rhizophagus irregularis*: This species is known for its ability to grow in a wide range of soil types, including heavy metal-contaminated soils. It prefers moderate to high levels of moisture and temperatures between 20-30°C.

iii. *Pisolithus tinctorius:* This species has been shown to be effective in absorbing heavy metals such as lead and cadmium. It prefers moderate to high levels of moisture and temperatures between 15-30°C.

iv. *Scleroderma citrinum*: This species is known for its ability to grow in soils with high levels of heavy metal contamination, including lead and cadmium. It prefers moderate to high levels of moisture and temperatures between 15-25°C.

v. *Funneliformis mosseae*: This species is known for its ability to absorb high levels of heavy metals, including zinc and copper. It prefers moderate to high levels of moisture and temperatures between 20-30°C.

5.4 Other limitations and challenges

These includes

i. Lack of understanding of mycorrhizal fungi: Despite their potential for bioremediation, there is still a lack of understanding of the mechanisms behind the accumulation of heavy metals by mycorrhizal fungi. This lack of understanding makes it difficult to predict how effective mycorrhizal fungi will be in removing heavy metals from contaminated soils and how best to use them for bioremediation purposes.

ii. Selective accumulation: Mycorrhizal fungi can absorb a wide range of heavy metals, but their ability to do so varies depending on the type of metal and the species of fungus involved. Some fungi may be better at absorbing certain heavy metals than others, and further research is needed to determine which species are best suited for bioremediation efforts.

iii. Incompatibility with certain plants: Not all plant species are compatible with mycorrhizal fungi, and the effectiveness of bioremediation may be reduced if the wrong species of fungus or plant is used. This highlights the need for careful selection of the appropriate species of mycorrhizal fungi and plants for each specific bioremediation project.

iv. Harvesting and extraction difficulties: Harvesting and extracting the accumulated heavy metals from mycorrhizal fungi can be challenging, especially if the fungi are deeply embedded in the soil. The process of harvesting and extracting heavy metals may also pose a risk to the environment and human health, and further research is needed to develop safe and effective methods.

v. Competition with other microorganisms: Mycorrhizal fungi are not the only microorganisms in the soil that can absorb heavy metals, and they may face competition from other microorganisms, such as bacteria and yeasts. This competition can reduce the overall effectiveness of bioremediation efforts, and further research is needed to understand the interactions between different microorganisms in contaminated soils.

6. Conclusion

Mycorrhizal fungi are known for their ability to form symbiotic relationships with plant roots and play a crucial role in bioremediation. The mutualistic relationship between mycorrhizal fungi and plants enables the former to effectively remediate contaminated environments by improving soil health and breaking down harmful pollutants. This is achieved through the secretion of enzymes and other metabolic by-products that help degrade toxic compounds such as heavy metals, petroleum hydrocarbons, and other persistent organic pollutants.

The effectiveness of mycorrhizal fungi in bioremediation has been demonstrated through numerous studies and field trials. The remarkable ability of these organisms to tolerate and degrade toxic compounds makes them ideal candidates for environmental clean-up efforts. Thus, the symbiotic relationship between mycorrhizal fungi and plants holds great promise for a cleaner and healthier planet. As more research is conducted, we can expect to unlock the full potential of these tiny but powerful organisms and continue to harness their benefits for bioremediation and environmental protection.

References

Adams, G. O., Fufeyin, P. T., Okoro, S. E., & Ehinomen, I. (2015). Bioremediation, biostimulation and bioaugmention: a review. *International Journal of Environmental Bioremediation & Biodegradation*, *3*(1), 28-39.

Anastasi, A., Tigini, V., & Varese, G. C. (2012). The bioremediation potential of different ecophysiological groups of fungi. In *Fungi as Bioremediators* (pp. 29-49). Berlin, Heidelberg: Springer Berlin Heidelberg.

Azubuike, C. C., Chikere, C. B., & Okpokwasili, G. C. (2016). Bioremediation techniques–classification based on site of

application: principles, advantages, limitations and prospects. *World Journal of Microbiology and Biotechnology*, *32*, 1-18.

Azubuike, C. C., Chikere, C. B., & Okpokwasili, G. C. (2016). Bioremediation techniques–classification based on site of application: principles, advantages, limitations and prospects. *World Journal of Microbiology and Biotechnology*, *32*, 1-18.

Baruah, G., & Sahu, J. (2019). A systematic review on the role of mycorrhiza in soil genesis using scientometrics analysis. *Mycorrhizosphere and Pedogenesis*, 95-109.

Berruti, A., Borriello, R., Orgiazzi, A., Barbera, A. C., Lumini, E., & Bianciotto, V. (2014). Arbuscular mycorrhizal fungi and their value for ecosystem management. *Biodiversity: the dynamic balance of the planet. InTech, Rijeta, Croacia*, 159-191.

Dutta, S. D., & Hyder, M. D. (2019). Mycoremediation: A potential tool for sustainable management. *Journal of Mycopathological Research*, *57*(1), 25-34.

Espinoza-Tofalos, A., Alviz-Gazitua, P., Franzetti, A., & Seeger, M. (2020). Bio-electrochemical remediation of petroleum hydrocarbons. Bioelectrochemical Systems: *Current and Emerging Applications, 2*, 269-285.

Haripriyan, U., Gopinath, K. P., Arun, J., & Govarthanan, M. (2022). Bioremediation of organic pollutants: A mini review on current and critical strategies for wastewater treatment. *Archives of Microbiology, 204*(5), 286.

Hashem, A., Abd_Allah, E. F., Alqarawi, A. A., & Egamberdieva, D. (2016). Bioremediation of adverse impact of cadmium toxicity on Cassia italica Mill by arbuscular mycorrhizal fungi. *Saudi Journal of Biological Sciences*, *23*(1), 39-47.

Hussain, A., Rehman, F., Rafeeq, H., Waqas, M., Asghar, A., Afsheen, N., ... & Iqbal, H. M. (2022). In-situ, Ex-situ, and nano-remediation strategies to treat polluted soil, water, and air–A review. *Chemosphere*, *289*, 133252.

Ilshadsabah, A., & Suchithra, T. V. (2019). Bacterial nanowires: an invigorating tale for future. *Microbial Nanobionics: Volume 2, Basic Research and Applications*, 77-88.

Jindal, T., & Thakur, M. (2019). Mushrooms as a biological tool in mycoremediation of polluted soils. *Emerging Issues in Ecology and Environmental Science: Case Studies from India,* 27-42.

Lai, A., Aulenta, F., Mingazzini, M., Palumbo, M. T., Papini, M. P., Verdini, R., & Majone, M. (2017). Bioelectrochemical approach for reductive and oxidative dechlorination of chlorinated aliphatic hydrocarbons (CAHs). *Chemosphere, 169*, 351-360.

Lone, R., Shuab, R., & Koul, K. K. (2016). AMF association and their effect on metabolite mobilization, mineral nutrition and nitrogen assimilating enzymes in saffron (Crocus sativus) plant. *Journal of Plant Nutrition*, *39*(13), 1852-1862.

Mishra, A., Bhattacharya, A., & Mishra, N. (2019). Mycorrhizal symbiosis: An effective tool for metal bioremediation. In *New and*

future developments in microbial biotechnology and bioengineering (pp. 113-128). Elsevier.
Orji, K. O., Eze, C. E., Harriman, C. J., Nwadinobi, C. A., Mbah, E. U., & Akpan, A. U. (2022) Mycorrhiza: A Potential Application for Increased Crop Productivity in a Degraded Soil. *Asian Journal of Advances in Agricultural Research, 19*(1). pp. 1-5
Padhan, D., Rout, P. P., Kundu, R., Adhikary, S., & Padhi, P. P. (2021). Bioremediation of heavy metals and other toxic substances by microorganisms. Soil bioremediation: *An approach towards sustainable technology*, 285-329.
Pandey, D., Kehri, H. K., Zoomi, I., Akhtar, O., & Singh, A. K. (2019). Mycorrhizal fungi: Biodiversity, ecological significance, and industrial applications. *Recent Advancement in White Biotechnology Through Fungi: Volume 1: Diversity and Enzymes Perspectives*, 181-199.
Pandey, N., Chandra, J., Xalxo, R., & Sahu, K. (2021). Concept and types of phytoremediation. In: Hasanuzzaman, M. (eds) Approaches to the Remediation of Inorganic Pollutants. *Springer, Singapore.* https://doi.org/10.1007/978-981-15-6221-1_14
Riaz, M., Kamran, M., Fang, Y., Wang, Q., Cao, H., Yang, G., ... & Wang, X. (2021). Arbuscular mycorrhizal fungi-induced mitigation of heavy metal phytotoxicity in metal contaminated soils: A critical review. *Journal of Hazardous Materials*, *402*, 123919.
Rimington, W. R., Pressel, S., Duckett, J. G., Field, K. J., Read, D. J., & Bidartondo, M. I. (2018). Ancient plants with ancient fungi: liverworts associate with early-diverging arbuscular mycorrhizal fungi. *Proceedings of the Royal Society B*, *285*(1888), 20181600.
Saeed, M. U., Hussain, N., Sumrin, A., Shahbaz, A., Noor, S., Bilal, M., ... & Iqbal, H. M. (2022). Microbial bioremediation strategies with wastewater treatment potentialities–A review. *Science of the total environment, 818,* 151754.
Srivastava, S. (2015). Bioremediation technology: A greener and sustainable approach for restoration of environmental pollution. *Applied Environmental Biotechnology: Present Scenario and Future Trends*, 1-18.
Tomer, A., Singh, R., Singh, S. K., Dwivedi, S. A., Reddy, C. U., Keloth, M. R. A., & Rachel, R. (2021). Role of fungi in bioremediation and environmental sustainability. *Mycoremediation and Environmental Sustainability, 3*, 187-200.
Verma, S., & Kuila, A. (2019). Bioremediation of heavy metals by microbial process. *Environmental Technology & Innovation, 14*, 100369.
Wang, F., Adams, C. A., Yang, W., Sun, Y., & Shi, Z. (2020). Benefits of arbuscular mycorrhizal fungi in reducing organic contaminant residues in crops: Implications for cleaner agricultural production. *Critical Reviews in Environmental Science and Technology*, *50*(15), 1580-1612.
Yadav, N., Kumar, N., Kumar, A., Devi, S., Kaur, V., Kumar, S., & Arya, S. S. (2022). Arbuscular Mycorrhizal Fungi: A Potential Candidate for

Nitrogen Fixation. In *Plant Stress Mitigators: Action and Application* (pp. 217-234). Singapore: Springer Nature Singapore.